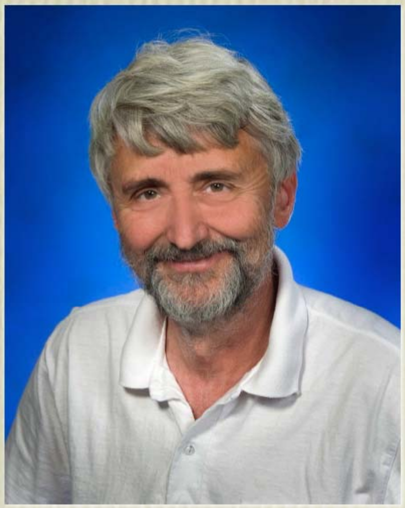
Paradigm Lost

What Spin did to the Quark Model

(or why we do experiments and

don't just listen to theorists)

- The rise and fall of an old paradigm
- The quark model paradigm 
- What the quark model said about spin
- What spin said about the quark model 
- Where we are now 



• The spin of the nucleon before quarks

Two theorists collaborated in the discovery of the spin of the proton!

- ★ 1927 David Dennison interprets the specific heat of molecular hydrogen in terms of two allotropic forms (ortho- and para-hydrogen)
- ★ 1927 Werner Heisenberg explains the degeneracy factors using his new quantum mechanics.
- ★ 1932 Werner Heisenberg wins the Nobel Prize with this citation

"for the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen."

A Note on the Specific Heat of the Hydrogen Molecule.

By David M. Dennison, Ph.D., University of Michigan.

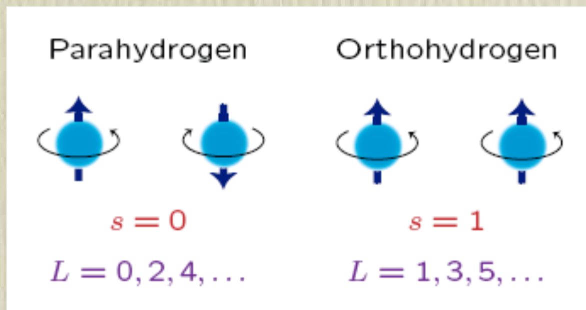
(Communicated by R. H. Fowler, F.R.S.—Received June 3, 1927.)

[*Added June* 16, 1927.—It may be pointed out that the ratio of 3 to 1 of the antisymmetrical and symmetrical modifications of hydrogen, as regards the rotation of the molecule, is just what is to be expected from a consideration of the equilibrium at ordinary temperatures if the nuclear spin is taken equal to that of the electron, and only the complete antisymmetrical solution of the Schrödinger wave equation allowed.*

While it would not appear possible to produce only the one modification of

the University of Michigan.

* W. Heisenberg, 'Z. f. Physik,' vol. 41, p. 239 (1927), in particular see p. 264.



Proceedings of the Royal Society of London. Series A, 115, 483-486 (1927).

- And it was quickly realized that the proton and neutron were not elementary

  - ⋆ In 1933 Otto Stern (I. Estermann and R. Frisch) measured the magnetic moment of the proton and found that its g-factor is not 2 as expected for an elementary Dirac fermion.
  - ⋆ Instead Stern found

$$\boldsymbol{\mu}_p = 2(\sim 2.5)\frac{e}{2Mc}\boldsymbol{s}_p$$

  - ⋆ In 1940 Luis Alvarez and Felix Bloch (another theorist) first measured the neutron magnetic moment and found

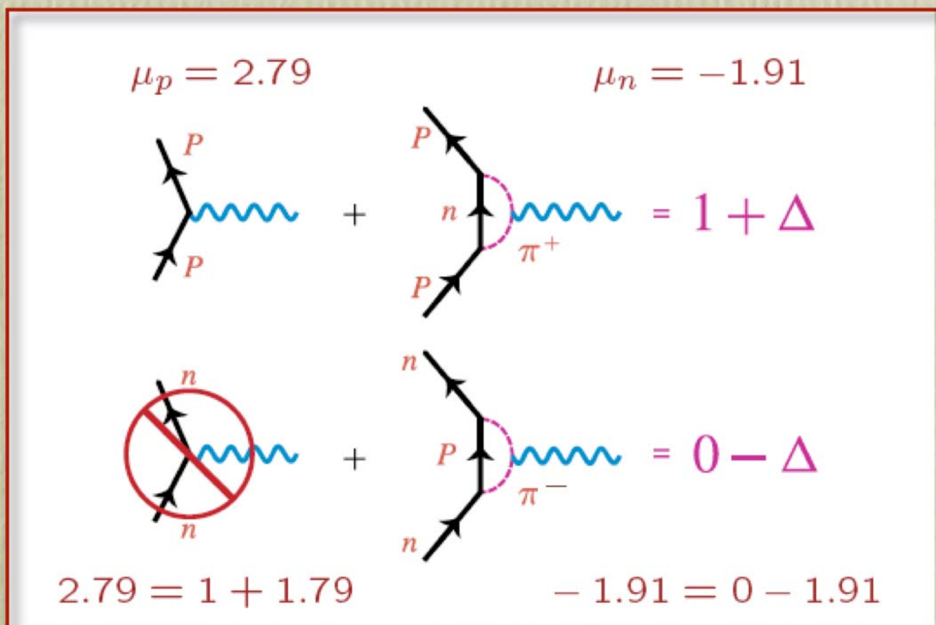
$$\boldsymbol{\mu}_n = 2(-1.93 \pm 0.02)\frac{e}{2Mc}\boldsymbol{s}_n$$

  - ⋆ Both commented on “other causes underly their magnetic properties”.

- And a successful paradigm for proton/neutron interactions soon emerged

⋆ Hideki Yukawa proposed a field theory of proton and neutron interactions in 1935 and predicted the existence of the pion.

⋆ And first order perturbation theory in Yukawa's theory nicely accounts for the proton and neutron magnetic moments!



A little more carefully

⋆ General photon coupling is a sum of isoscalar and isovector. $Q = I_3 + Y/2$

⋆ But photon coupling to pion is pure isovector ($Y = 0$).

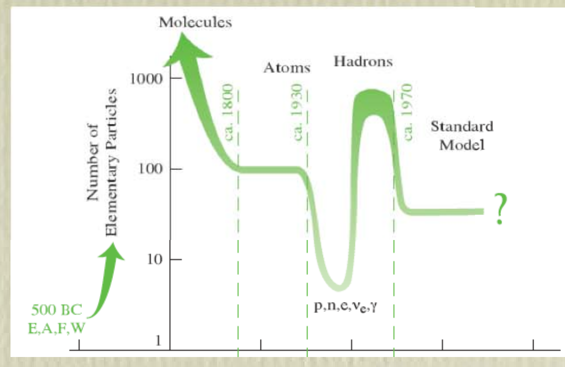
⋆ So "pion cloud" contribution to nucleon magnetic moments is pure isovector:

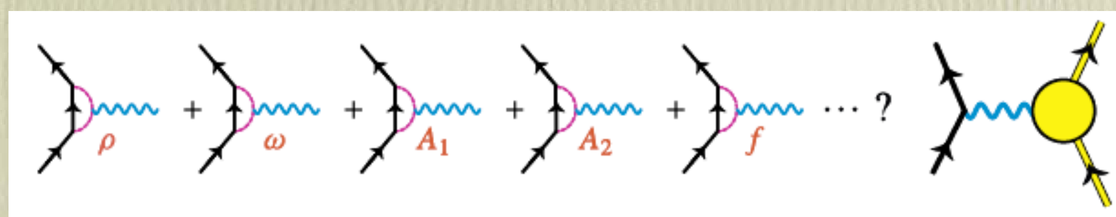
Equal and opposite for p and n

- The proton-neutron-pion paradigm does pretty well!

  ★ The number of "elementary particles" hit a minimum at the time of Yukawa's paradigm

proton	**electron**
neutron	**electron-anti- neutrino**
pion	**photon**
	muon





  ★ But hadrons proliferated, and

  ★ Interactions are strong, so first order perturbation theory is not justified

  ★ And contributions of heavier mesons could not be controlled

  ★ So the paradigm fell

  Not from contradiction, but from inability to make reliable predictions

- And a new paradigm emerged based on QCD, asymptotic freedom, and the quark model

★ $SU(3)_f \rightarrow$ QUARKS $\rightarrow$ CURRENT ALGEBRA $\rightarrow$ PARTON MODEL $\rightarrow$ QCD

★ A simple starting point

$$
\begin{aligned}
|p\uparrow\rangle &= \frac{1}{\sqrt{6}}\left|2u^\uparrow u^\uparrow d^\downarrow - u^\uparrow u^\downarrow d^\uparrow - u^\downarrow u^\uparrow d^\uparrow\right\rangle \\
|n\uparrow\rangle &= \frac{1}{\sqrt{6}}\left|2d^\uparrow d^\uparrow u^\downarrow - d^\uparrow d^\downarrow u^\uparrow - d^\downarrow d^\uparrow u^\uparrow\right\rangle
\end{aligned}
$$

★ Compute baryon magnetic moments in terms of quark magnetic moments

$$
\begin{aligned}
\mu_p &= \mu_u \\
\mu_n &= -\frac{2}{3}\mu_u \\
\mu_\Lambda &= -\frac{1}{3}\mu_s
\end{aligned}
$$

Precise Measurement of the Λ^0 Magnetic Moment

L. Schachinger,[a] G. Bunce,[b] P. T. Cox, T. Devlin, J. Dworkin, B. Edelman,[c] R. T. Edwards,[d] R. Handler, K. Heller,[e] R. March, P. Martin,[f] O. E. Overseth, L. Pondrom, M. Sheaff, and P. Skubic

Physics Department, University of Michigan, Ann Arbor, Michigan 48109, and Physics Department, Rutgers —The State University, Piscataway, New Jersey 08854, and Physics Department, University of Wisconsin, Madison, Wisconsin 53706

(Received 8 September 1978)

The magnetic moment of the Λ^0 hyperon has been measured to be $\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N$.

[a]Now at Enrico Fermi Institute, Chicago, Ill. 60637.
[b]Now at Brookhaven National Laboratory, Upton, N. Y. 11973.
[c]Now at Ford Motor Company, Allen Park, Mich. 48101.

- ⋆ Assign masses to quarks

  $m_u \sim M_N/3 \qquad m_s/m_u > 1$

  Very good fit to 8 baryon magnetic moments plus $\Lambda \leftrightarrow \Sigma$ dipole transition.

- ⋆ Gerry's measurement of the Λ magnetic moment was (and still is) one of the strong pieces of evidence that we understand quark spin/charge correlation in baryons

- ⋆ Quark description of baryon spin seemed to be in very good shape

  (In retrospect: For charge correlated spin (which is C-odd and flavor non-singlet),

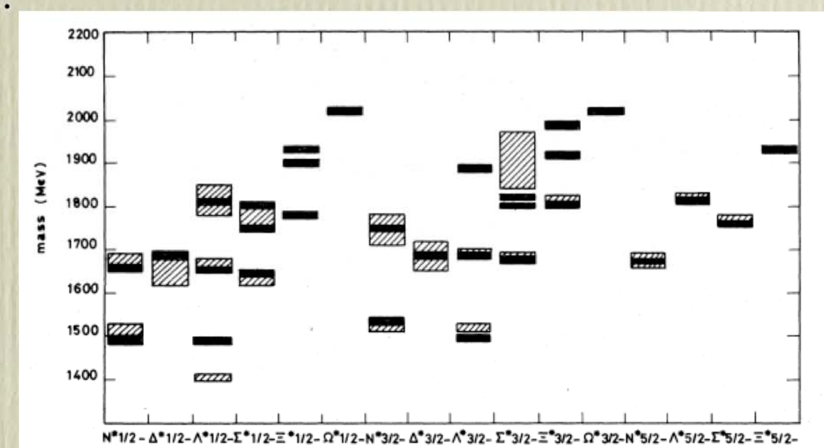
  and for $\boldsymbol{r} \times \bar{q}\gamma q$ not $\bar{q}\gamma\gamma_5 q$)

- ⋆ Non-relativistic quark model program of Dalitz, Isgur & Karl, created a zeroth order paradigm for a quark description of hadrons.

- ⋆ **Baryon spectrum**

  Static E& M and Weak Moments

  Electromagnetic transitions



N. Isgur and G. Karl: P-wave baryons Phys. Rev. **D18**, 4187 (1978).

- Meanwhile the pedigree of the quark paradigm improved steadily

  ⋆ In 1964 few took quarks seriously.

  ⋆ 1965 – 1972 Current Algebra (Adler, Weisberger, Dashen, Gell-Mann, Bjorken,...)

  predecessor of OPERATOR PRODUCT EXPANSION

  ⋆ Quark light-cone algebra ≡ Parton model

  predecessor of RENORMALIZATION GROUP

$$\frac{1}{2}\int_0^1 dx\,\left(F_1^{\bar{\nu}p}(x) - F_1^{\nu p}(x)\right) = I_3 \qquad \text{Adler Sum Rule (quark isospin)}$$

$$\frac{1}{2}\int_0^1 dx\,\left(F_3^{\nu p}(x) + F_3^{\bar{\nu}p}(x)\right) = -3B \qquad \text{Gross-Llewellyn Smith SR (quark baryon number)}$$

  ⋆ Quark model embedded in emerging theory of hadrons — QCD

  ⋆ Relativistic improvements to quark models, bag models, flux tube models, ...

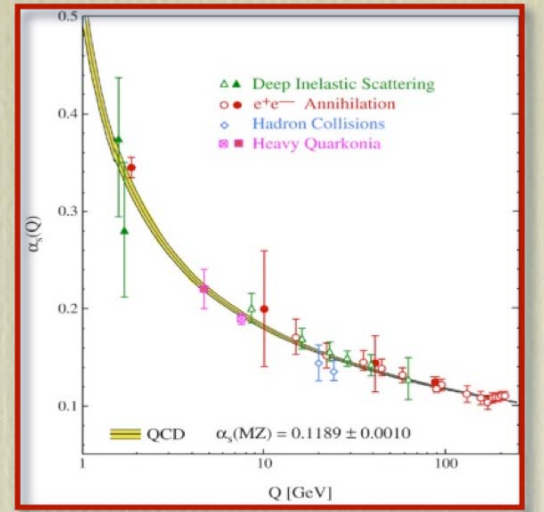
  ⋆ QCD - quark model synthesis: De-evolution from asymptotic Q^2 to $\Lambda_{\rm QM}$ where nucleon is three "constituent quarks". α_s is still small up till confinement. (Deserves more explanation...)

A “hard wall” embedding of the quark model paradigm in QCD

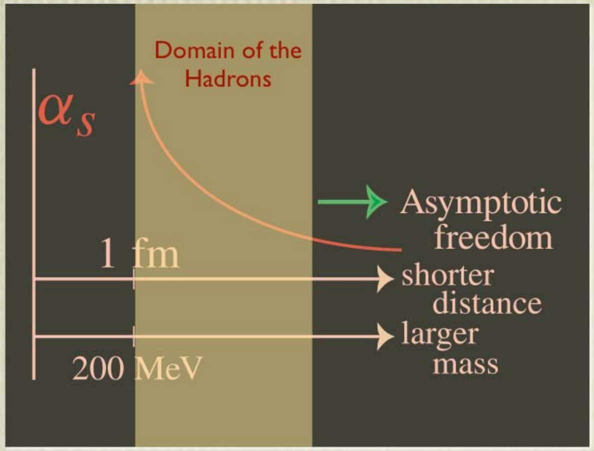
- ⋆ $\alpha_s(Q^2)$ grows toward strong coupling in the infrared.
- ⋆ But running is cut off by confinement at a hadronic scale.
- ⋆ One could hope that non-perturbative, strong-coupling phenomena in QCD can be successfully amalgamated into a (relatively) simple confining potential — relativistically, a “bag”!
- ⋆ Parton distributions at asymptotic Q^2 devolve to effective constituent quark degrees of freedom in the infrared.
- ⋆ RLJ & Ross Phys. Lett. **B93**, 313 (1980).

  Glück and Reya Phys. Rev. **D 28**, 2749 - 2755 (1983).

  Shifman & collaborators



Siegfried Bethke, arXiv:hep-ex/0606035



- Dark clouds on the distant horizon

The nucleon spin in the non-relativistic quark model

★ Neutron axial vector coupling constant:

$$\langle \boldsymbol{s}_p | \sum_j (\boldsymbol{\sigma} I_3)_j \, | \boldsymbol{s_p} \rangle = \frac{g_A}{g_V} \boldsymbol{s}_p = \frac{5}{3} \boldsymbol{s}_p$$

Experiment $g_A/g_V = 1.2695(27)$

★ Quark model rules for deep inelastic electron scattering (pre-1973)

$$\begin{aligned}
\int_0^1 dx\, g_1^{ep}(x) \boldsymbol{s}_p &= 6 \, \langle \boldsymbol{s}_p | \sum_j (\boldsymbol{s} Q^2)_j \, | \boldsymbol{s_p} \rangle = \left(\frac{5}{3}\right) \boldsymbol{s}_p \\
\int_0^1 dx\, g_1^{en}(x) \boldsymbol{s}_n &= 6 \, \langle \boldsymbol{s}_n | \sum_j (\boldsymbol{s} Q^2)_j \, | \boldsymbol{s_n} \rangle = (0) \, \boldsymbol{s}_n
\end{aligned}$$

★ Reproduces unsuccessful prediction of g_A/g_V and makes strong (and as it turns out, wrong) prediction for neutron

- ⋆ Quark spin operator:

$$\Delta Q_a s_\mu = \langle Ns|\bar{q}_a\gamma_\mu\gamma_5 q_a|Ns\rangle$$

$$\Delta\Sigma = \Delta U + \Delta D + \Delta S$$

- ⋆ $\bar{q}\gamma_k\gamma_5 q$ is the generator of the internal rotations of the quark field about the $\hat{e}_k$ direction.
- ⋆ Nonrelativistic limit:

$$\rightarrow q^\dagger\sigma_k q$$

- ⋆ But how to measure??
- ⋆ β-decay, parity violating coupling measures certain combinations of ΔQ's:
  - $F + D = \Delta U - \Delta D$ measured in nucleon β decay.
  - $2F = \Delta U - \Delta S$ in hyperon (Λ, Σ, ...) β decay.

$$F + D = 1.257 \pm 0.003$$
$$3F - D = 0.60 \pm 0.05$$

- ⋆ A better idea (M. Gourdin): Relate matrix elements on the right hand side to octet baryon axial vector charges.

  Avoid misprediction of g_A/g_V, and relate to measurable β-decay charges.

- ⋆ However, exactly the combination that measures the total quark spin is the combination that decouples from β decay!

$$\boxed{\begin{aligned}\Delta\Sigma &= \Delta U + \Delta D + \Delta S \\ &= 3F - D + 3\Delta S\end{aligned}}$$

!

“Strong” Zweig Rule

- Hadrons contain only those quarks required by their flavor content
- Gell-Mann – CALT-68-244 (unpub); J. Kim & F. von Hippel PRL **22** 740 (1969); G. Segré PR **D3**, 1954 (1971)
- Suggests $\Delta S = 0$

Retrospectively

★ $\Delta S = 0$ is a scale dependent assertion – can only hold at one value of Q^2.

Presumably $Q^2 \sim \Lambda^2_{\text{hadronic}}$

★ But it sharpened the issue

J. Ellis & RLJ (1973):

Assume $\Delta S = 0$ “No polarized s-quarks in the nucleon”

★ Gives predictions for both proton and neutron sum rules

★ Gives prediction for $\Delta\Sigma$ in terms of β decay data:

$$\begin{aligned}\Delta\Sigma &= 3F - D + 3\Delta S \\ &\Rightarrow 3F - D \\ &= 0.60 \pm 0.05\end{aligned}$$

- STRIKE ONE --- either
  1. Quark spin carries only 60% of the nucleon spin
  2. Or the strange quarks in the nucleon give a significant, positive contribution to the nucleon spin

Context, consequences, experimental program

★ Quark spin sum rule from DIS

★ L. M. Sehgal (1974) Proposed that quark orbital angular momentum accounted for spin deficit

★ Relativistic quark (bag) models accounted for both spin and g_A/g_V with the same mechanism

Dirac ground state has orbital angular momentum

★ Raised many questions about NRQM, but on balance improved the quark paradigm

Deep Inelastic Scattering

★ $ep \to e'X$ – quasi-elastic scattering from quarks – the process by which quarks were discovered at SLAC by Friedman, Kendall, Taylor, & co., in 1968.

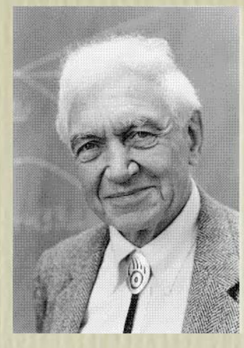
★ Gives sum rules for polarized scattering

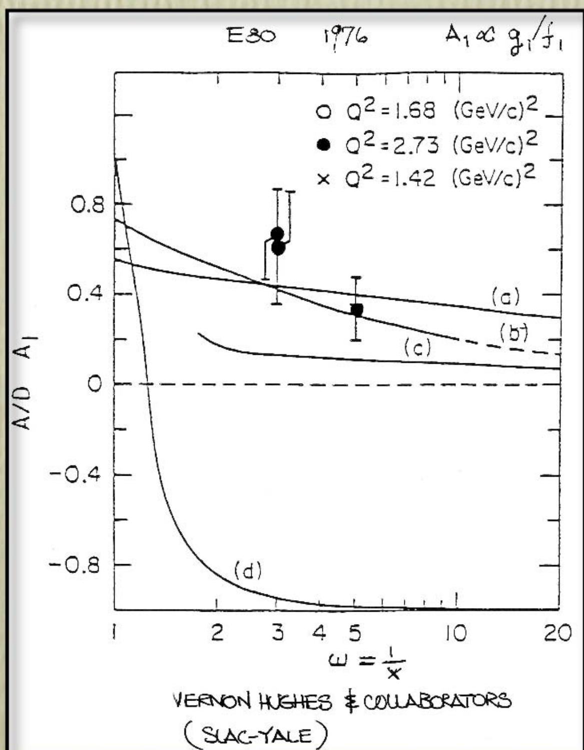
$$\int_0^\infty dx\, g_1^{\mathrm{ep}}(x,Q^2) = \tfrac{1}{18}(9F - D + 6\Delta s) = \tfrac{1}{18}(3F + D + 2\Delta\Sigma)$$

$$\int_0^\infty dx\, g_1^{\mathrm{en}}(x,Q^2) = \tfrac{1}{18}(6F - 4D + 6\Delta s) = \tfrac{1}{18}(-2D + 2\Delta\Sigma)$$

First steps in an experimental program

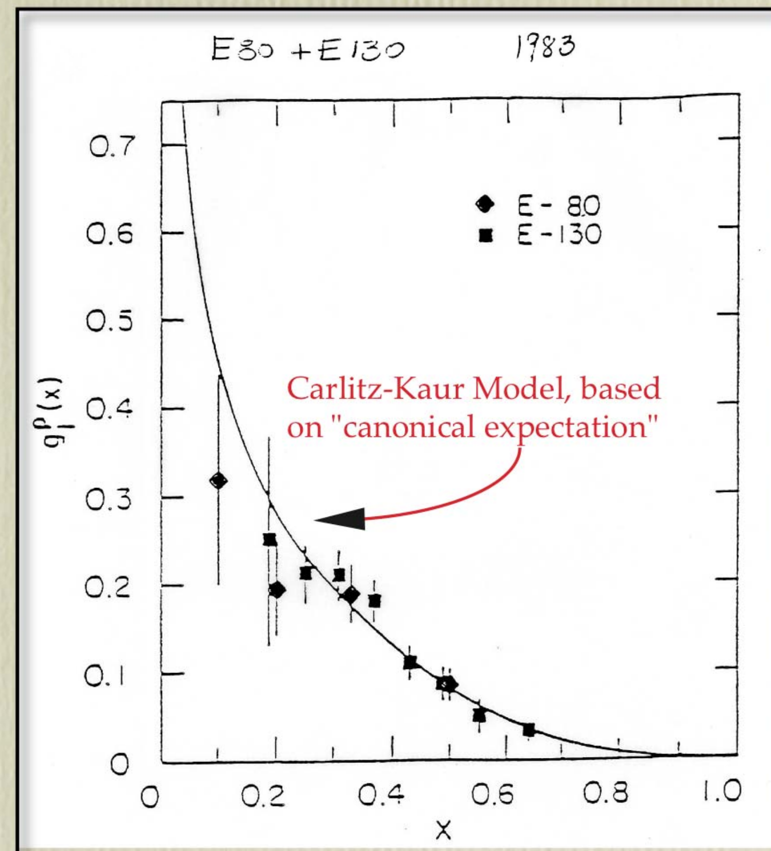
- ⋆ V. Hughes and collaborators (Yale, SLAC)
- ⋆ E80 – 1976
- ⋆ E130 – 1980
- ⋆ Consistent with $\Delta S = 0 + \beta$-decay (EJSR)





1976 E 080

Yale: G. Baum, R. Ehrlich, A. Etkin, V. W. Hughes, D. Lu, M. Lubell, W. Raith, P. Souder, M. Zeller
NSF: J. Sanderson
SLAC: D. Coward, D. Sherden, C. Sinclair
MIT: J. Kuti



- Meanwhile --- more clouds gather on the horizon!

#1 Large polarization observed in high energy Λ production

And who should be there, but ...

Λ^0 **Hyperon Polarization in Inclusive Production by 300-GeV Protons on Beryllium**

G. Bunce, R. Handler, R. March, P. Martin, L. Pondrom, and M. Sheaff
Physics Department, University of Wisconsin, Madison, Wisconsin 53706*

and

K. Heller, O. Overseth, and P. Skubic
Physics Department,† University of Michigan, Ann Arbor, Michigan 48104

and

T. Devlin, B. Edelman, R. Edwards, J. Norem, L. Schachinger, and P. Yamin
Physics Department,† Rutgers University, New Brunswick, New Jersey 08903
(Received 1 December 1975)

Λ^0 polarization has been observed in $p + \mathrm{Be} \to \Lambda^0 +$ anything at 300 GeV. A total of 1.2×10^6 Λ^0 decays were recorded at fixed lab angles between 0 and 9.5 mrad, covering a range of kinematic variables $0.3 \le x \le 0.7$ and $0 \le p_\perp \le 1.5$ GeV/c. The observed polarization was consistent with parity conservation and increased monotonically with increasing $p_\perp$, independently of x, reaching $P_\Lambda = 0.28 \pm 0.08$ at 1.5 GeV/c.

Polarization of Λ's and $\bar{\Lambda}$'s Produced by 400-GeV Protons

K. Heller, P. T. Cox, J. Dworkin, O. E. Overseth, and P. Skubic[a]
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and

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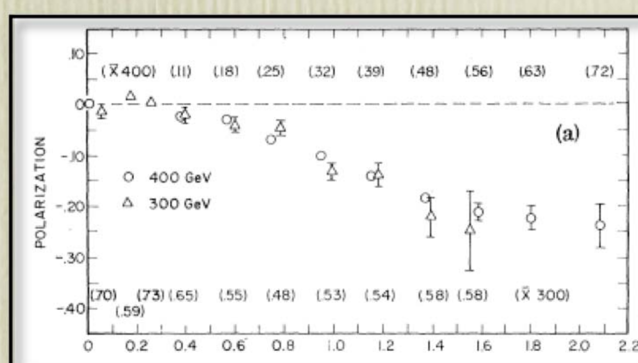
and

G. Bunce,[d] R. Handler, R. March, P. Martin,[c] L. Pondrom, and M. Sheaff
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
(Received 5 June 1978)

★ Transverse spin effects were supposed to be suppressed at high energy/momentum in QCD

★ Λ-polarization was expected to be small in quark models



#2

Elastic scattering at fixed angle and moderate energies show large and largely inexplicable polarization effects

- ⋆ Program began at ANL in early 1970's
- ⋆ Moved to BNL in 1980's and continued to higher energies
- ⋆ Fixed angle elastic $p^\uparrow p^\uparrow$ scattering
- ⋆ Never could be properly analyzed in QCD
- ⋆ But effects were uncomfortably large
- ⋆ And the program brought spin physics expertise to BNL!

Energy dependence of spin-spin effects in p-p elastic scattering at $90^\circ_{c.m.}$

E. A. Crosbie, L. G. Ratner, and P. F. Schultz
Argonne National Laboratory, Argonne, Illinois 60439

J. R. O'Fallon
Argonne Universities Association, Argonne, Illinois 60439

D. G. Crabb, R. C. Fernow,* P. H. Hansen,† A. D. Krisch, A. J. Salthouse,‡ B. Sandler,§ T. Shima, and K. M. Terwilliger
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N. L. Karmakar
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Department of Physics and Center for Theoretical Studies, The University of Miami, Coral Gables, Florida 33124

P. Kyberd
Nuclear Physics Laboratory, Oxford University, Oxford, England

(Received 31 March 1980)

Measurement of Spin Effects in $p_\uparrow + p_\uparrow \to p + p$ at 18.5 GeV/c

D. G. Crabb, I. Gialas, A. D. Krisch, A. M. T. Lin, D. C. Peaslee, R. A. Phelps, R. S. Raymond, T. Roser, J. A. Stewart, and K. M. Terwilliger
Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan 48109

K. A. Brown, G. T. Danby, F. Z. Khiari, and L. G. Ratner
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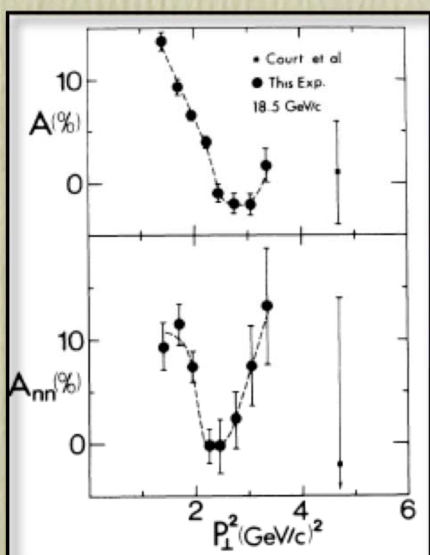
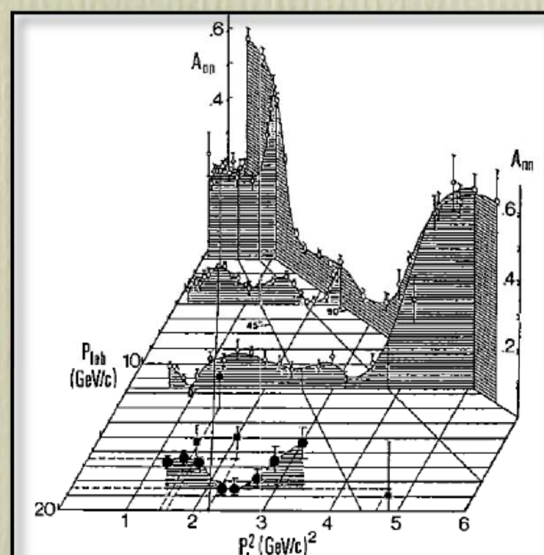
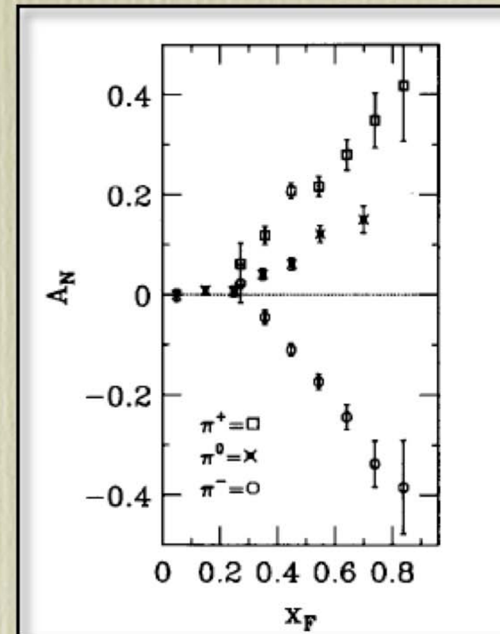
(Received 16 March 1988)





#3 Fermilab E704 — pion production by polarized protons shows huge spin asymmetries at large $p_\perp$

- ★ Transverse polarization effects in $p^\uparrow p$ scattering were supposed to vanish at large transverse momentum ("higher twist")
- ★ Suggest orbital angular momentum and/or spin-orbit correlation in the initial polarized proton state
- ★ And raised much interest in polarized hadron physics among a group of young experimental physicists, including many from Japan



Analyzing power in inclusive π^+ and π^- production at high x_F with a 200 GeV polarized proton beam

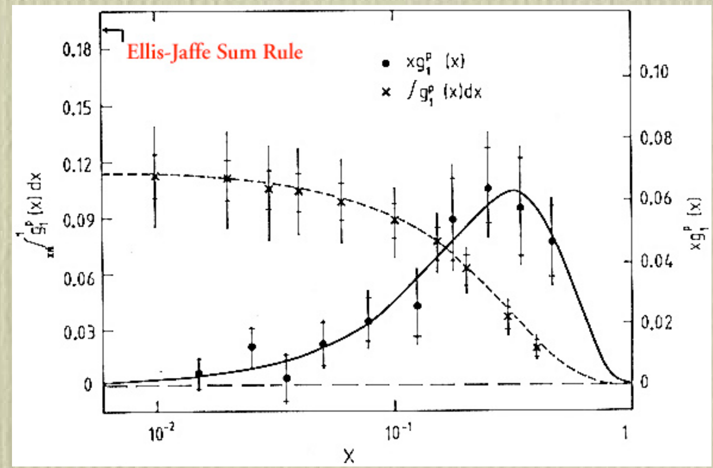
FNAL E704 Collaboration

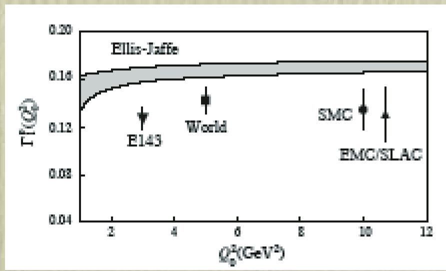
D.L. Adams [a], N. Akchurin [b], N.I. Belikov [c], B.E. Bonner [a], J.A. Buchanan [a], J. Bystricky [d], J.M. Clement[a], M.D. Corcoran [a], J.D. Cossairt [c], J. Cranshaw [a], A.A. Derevschikov [c], H. En'yo [f], H. Funahashi [f], Y. Goto [f], O.A. Grachov [c], D.P. Grosnick [g], D.A. Hill [g], K. Imai [f], Y. Itow [f], K. Iwatani [h], K.W. Krueger [i], K. Kuroda [j], J. Langland [b], F. Lehar [d], A. de Lesquen [d], D. Lopiano [g], F.C. Luehring [k,1], T. Maki [ℓ], S. Makino [f], A. Masaike [f], Yu.A. Matulenko [c], A.P. Meschanin [c], A. Michalowicz [j], D.H. Miller [k], K. Miyake [f], T. Nagamine [f,2], F. Nessi-Tedaldi [a,3], M. Nessi [a,3], C. Nguyen [a], S.B. Nurushev [c], Y. Ohashi [g], Y. Onel [b], D.I. Patalakha [c], G. Pauletta [m], A. Penzo [n], G.C. Phillips [a,4], A.L. Read [c], J.B. Roberts [a], L. van Rossum [g,e], V.L. Rykov [c], N. Saito [f], G. Salvato [o], P. Schiavon [n], J. Skeens [a], V.L. Solovyanov [c], H. Spinka [g], R.W. Stanek [g], R. Takashima [p], F. Takeutchi [q], N. Tamura [r], N. Tanaka [s], D.G. Underwood [g], A.N. Vasiliev [c], A. Villari [o], J.L. White [a], S. Yamashita [f], A. Yokosawa [g], T. Yoshida [t] and A. Zanetti [n]

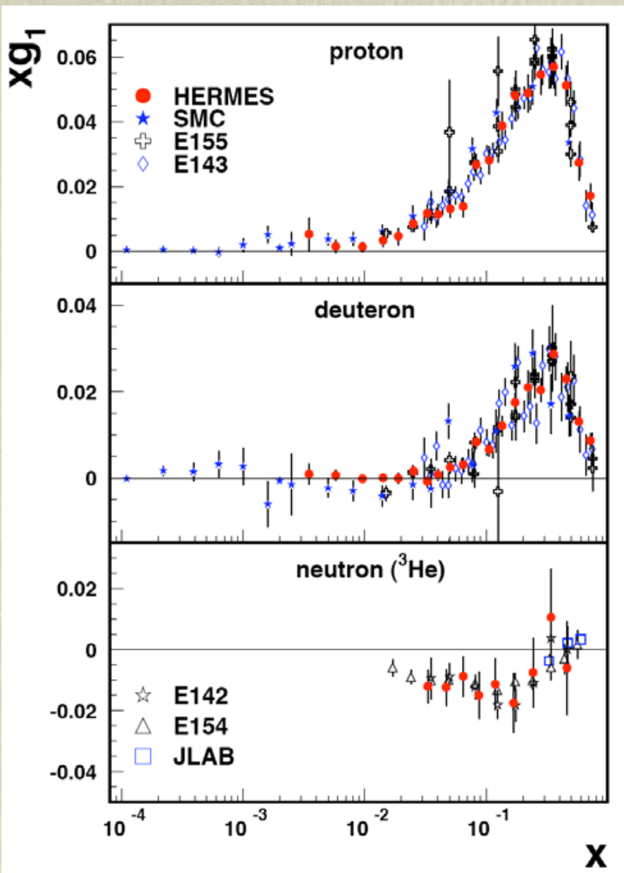
Significant contingent of Japanese physicists joining the U. S. spin program!

- STRIKE TWO --- Meanwhile back in polarized DIS
  1. Quarks carry only 25% of the nucleon spin
  2. There must be polarized strange quarks in the nucleon <u>oppositely correlated with nucleon spin</u> (or SU(3) must be unexpectedly violated in beta-decay)
  3. What does carry the spin of the nucleon?

Largely well known story around here!







- Situation at the time of the “Spin Crisis” -- 1987-- ?

Significant departure from canonical spin content

$$\begin{aligned} \Delta\Sigma &= 0.28 \pm 0.16 \\ \Delta U &= 0.82 \pm 0.05 \\ \Delta D &= -0.44 \pm 0.05 \\ \Delta S &= -0.10 \pm 0.05 \end{aligned}$$

★ $\approx 3/4$ of the nucleon spin is “elsewhere”

★ Focus on gluons

- In part justified
- And it motivated new spin physics programs to measure gluon spin in the nucleon
- However this ignored earlier speculations about orbital angular momentum
- Gave a jump start to deep inelastic spin physics at BNL

★ Theorists could catalogue contributions to the nucleon spin

★ And enumerate a myriad of new deep inelastic spin effects — many of enduring interest — Sivers function, Collins function, interference fragmentation function, Boer-Mulders function, ...

★ But we lost confidence in the quark model paradigm for hadron structure

- Dreaming of a polarized collider at RHIC

- ## Polarized collider at RHIC!
    - Polarized Collider Workshop, University Park, Pa., Nov 15-17, 1990
    - Particle World article "Polarized Protons at RHIC" 1992
    - Formation of RHIC Spin Collaboration
    - Special review NSAC (?) Review Panel at BNL
    - Formation of RIKEN-BNL Research Center founded at BNL in April 1997

Priorities

★ Measure ΔG in

$$\begin{aligned} p^{\uparrow}p^{\uparrow} &\to \pi^{\pm,0} + X \\ p^{\uparrow}p^{\uparrow} &\to \gamma + X \\ p^{\uparrow}p^{\uparrow} &\to \text{jet} + X \end{aligned}$$

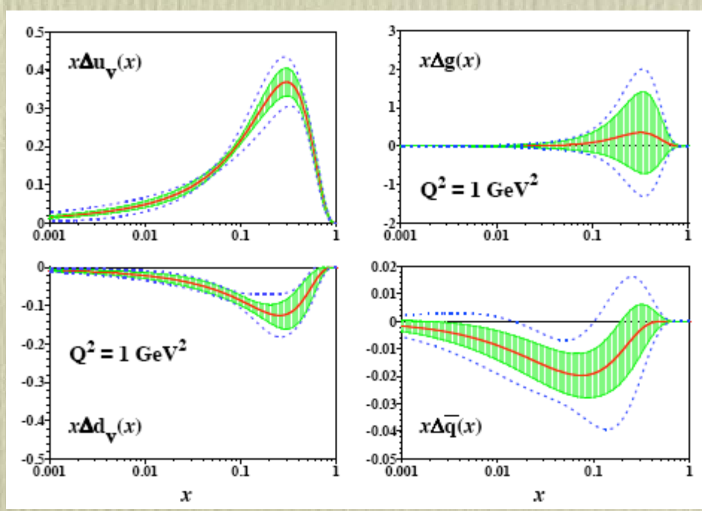
★ Measure $\overline{\Delta u}$ and $\overline{\Delta d}$ in $p^{\uparrow}p^{\uparrow} \to W^{\pm} + X$

★ Measure transverse asymmetries in $p^{\uparrow}p$ and $p^{\uparrow}p^{\uparrow}$.

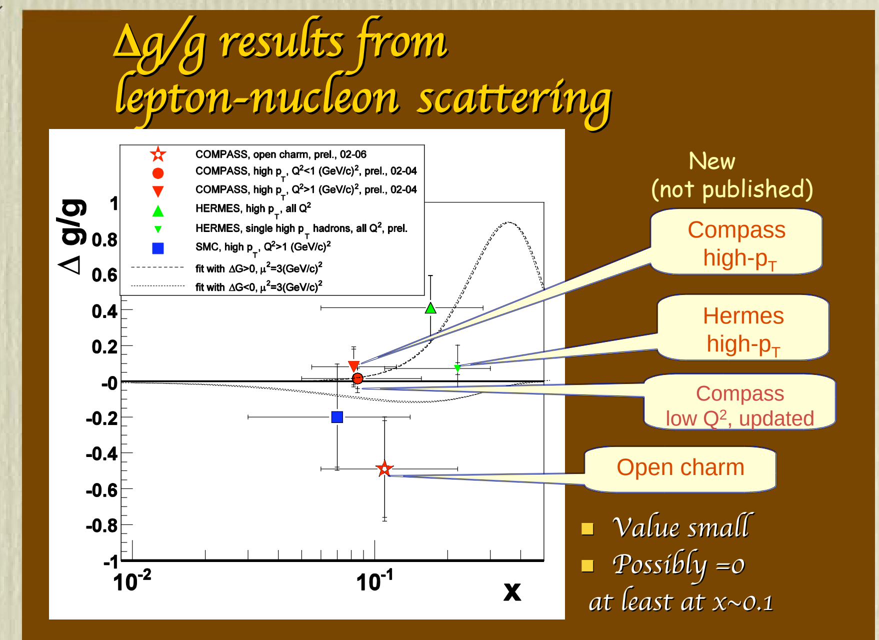
- STRIKE THREE ?? --- GLUONS SEEM NOT TO BE THE ANSWER
  1. Evolution analysis plus results from COMPASS, HERMES
  2. And STAR and PHENIX at RHIC
  3. What does carry the spin of the nucleon?

Gluon helicity distributions vigorously pursued in

- QCD evolution of quark DIS helicity distributions
- Charm or jet production in DIS (COMPASS & Hermes)
- $\pi^{+,-,0}$, jet, single-γ production in $p^{\uparrow}p^{\uparrow}$ at RHIC



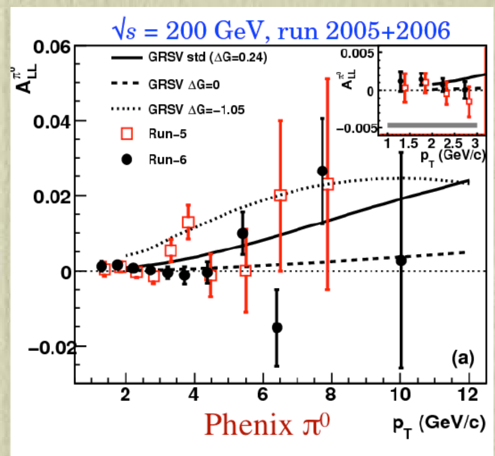
AAC (2003) evolution analysis, for example



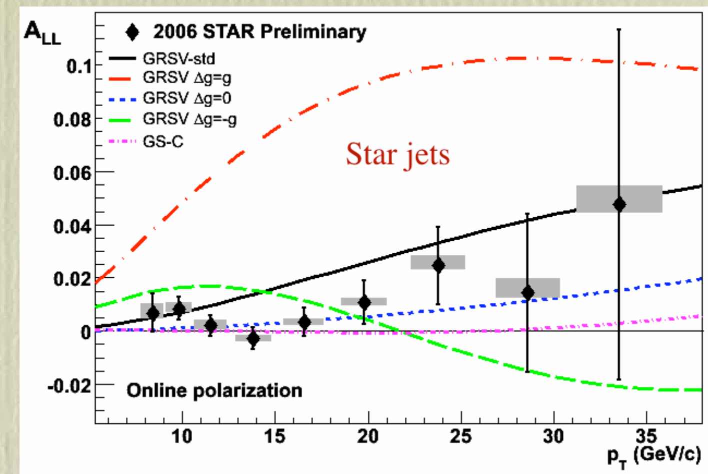
Ewa Rondio @ SPIN2008

Decisive data just beginning to become available from RHICSpin

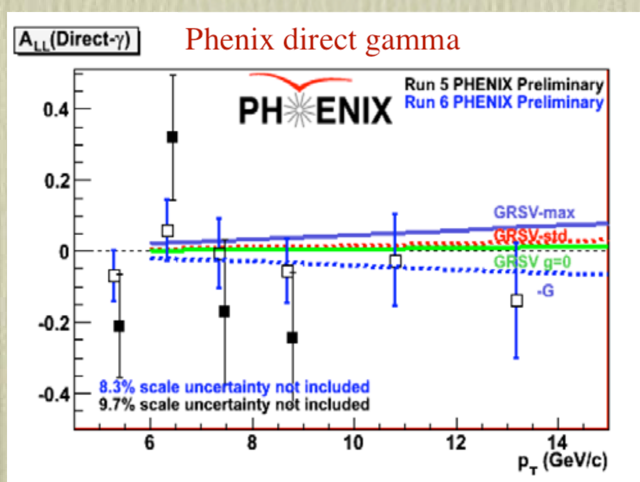
- Still low luminosity running
- Gluon polarizations are small
- Global analyses including DIS and RHIC at NLO now available...



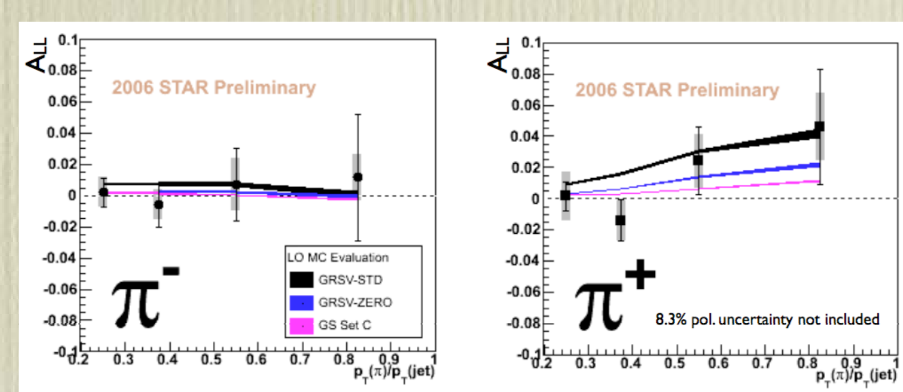
Phenix π^0



Star jets



Phenix direct gamma



Star $\pi^\pm$

De Florian, Sassot, Stratmann & Vogelsang (PRL **101**, 072001 (2008))

- Global
- DIS and collider
- NLO
- Integrated gluon spin is small

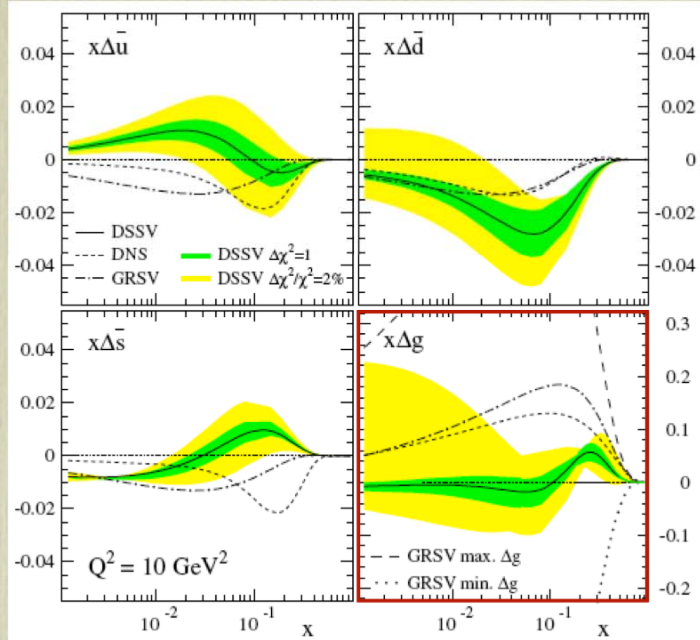


TABLE II. First moments $\Delta f_j^{1,[x_{\min}\to 1]}$ at $Q^2 = 10$ GeV^2.

	$x_{\min} = 0$ best fit	$x_{\min} = 0.001$ $\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793^{+0.011}_{-0.012}$	$0.793^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	−0.458	$-0.416^{+0.011}_{-0.009}$	$-0.416^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028^{+0.021}_{-0.020}$	$0.028^{+0.059}_{-0.059}$
$\Delta\bar{d}$	−0.115	$-0.089^{+0.029}_{-0.029}$	$-0.089^{+0.090}_{-0.080}$
$\Delta\bar{s}$	−0.057	$-0.006^{+0.010}_{-0.012}$	$-0.006^{+0.028}_{-0.031}$
Δg	−0.084	$0.013^{+0.106}_{-0.120}$	$0.013^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366^{+0.015}_{-0.018}$	$0.366^{+0.042}_{-0.062}$

So it is unlikely that gluons carry "the rest" of the nucleon's spin, and it is even possible that they are anti-correlated with the nucleon spin!

Pause — A spin audit

⋆ In the infinite momentum frame (RLJ & Manohar, Hägler & Schafer, Ravindranath & Kundu)

$$\frac{\mathbf{1}}{\mathbf{2}} = \boxed{\frac{\mathbf{1}}{\mathbf{2}}\boldsymbol{\Delta\Sigma} + \boldsymbol{\Delta G}} +$$

$$\boldsymbol{\Delta\Sigma} = \boldsymbol{\Delta u} + \boldsymbol{\Delta d} + \boldsymbol{\Delta s}$$

	NRQM < 1970	Weak Decays & $\Delta s = 0$ 1973	EMC 1989	Relativistic Quark Model	Present State 2008
$\Delta\Sigma$	1	0.60 ± 0.05	0.28 ± 0.16	α	0.21 ± 0.06
Δu	$\frac{4}{3}$	0.92 ± 0.03	0.82 ± 0.05	$\frac{4}{3}\alpha$	0.78 ± 0.03
Δd	$-\frac{1}{3}$	-0.32 ± 0.03	-0.44 ± 0.05	$-\frac{1}{3}\alpha$	-0.47 ± 0.03
Δs	0	0	-0.10 ± 0.05	0	-0.09 ± 0.03
ΔG	0	?		0	≈ -0.084
ΔL_q	0	$+0.40?$		$\Delta L_u = \frac{4}{3}(1-\alpha)$ $\Delta L_d = -\frac{1}{3}(1-\alpha)$	?
ΔL_g	0	?			?

Pause — A spin audit

- ⋆ In the infinite momentum frame (RLJ, Hägler & Schafer, Ravindranath & Kundu)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G +$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

- ⋆ In the “lab frame” (RLJ, Manohar, Ji)

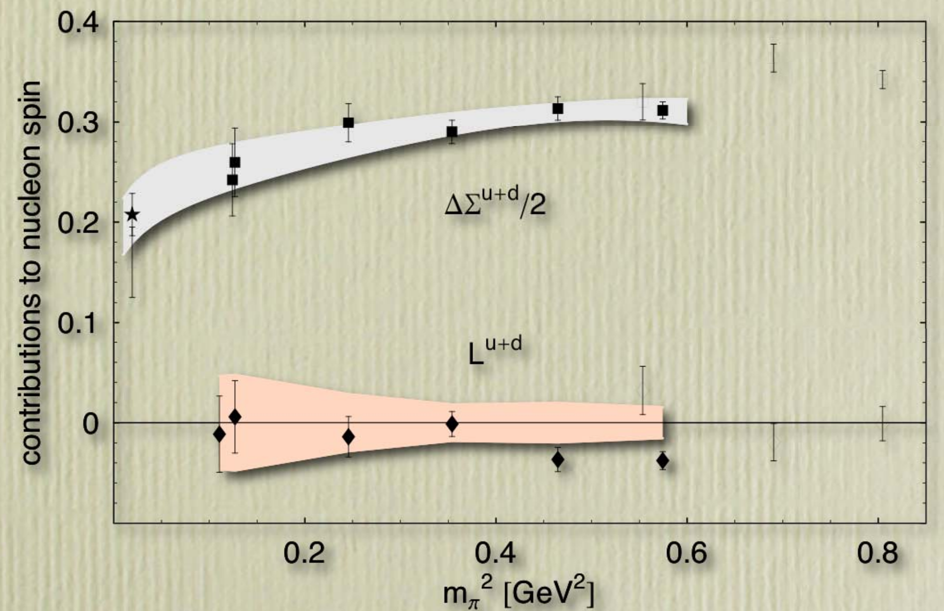
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \boxed{\Delta\mathcal{L}_q} + \mathcal{J}_g$$

- STRIKE FOUR (“4 strikes and you’re out!”)

  Lattice calculations of orbital angular momentum don’t seem to make sense from a quark model perspective!

  - ⋆ First lattice QCD calculation of $\langle \mathcal{L}_q \rangle$ for u and d quarks.
  - ⋆ First (mild) surprise: Quark orbital angular momentum is consistent with zero.

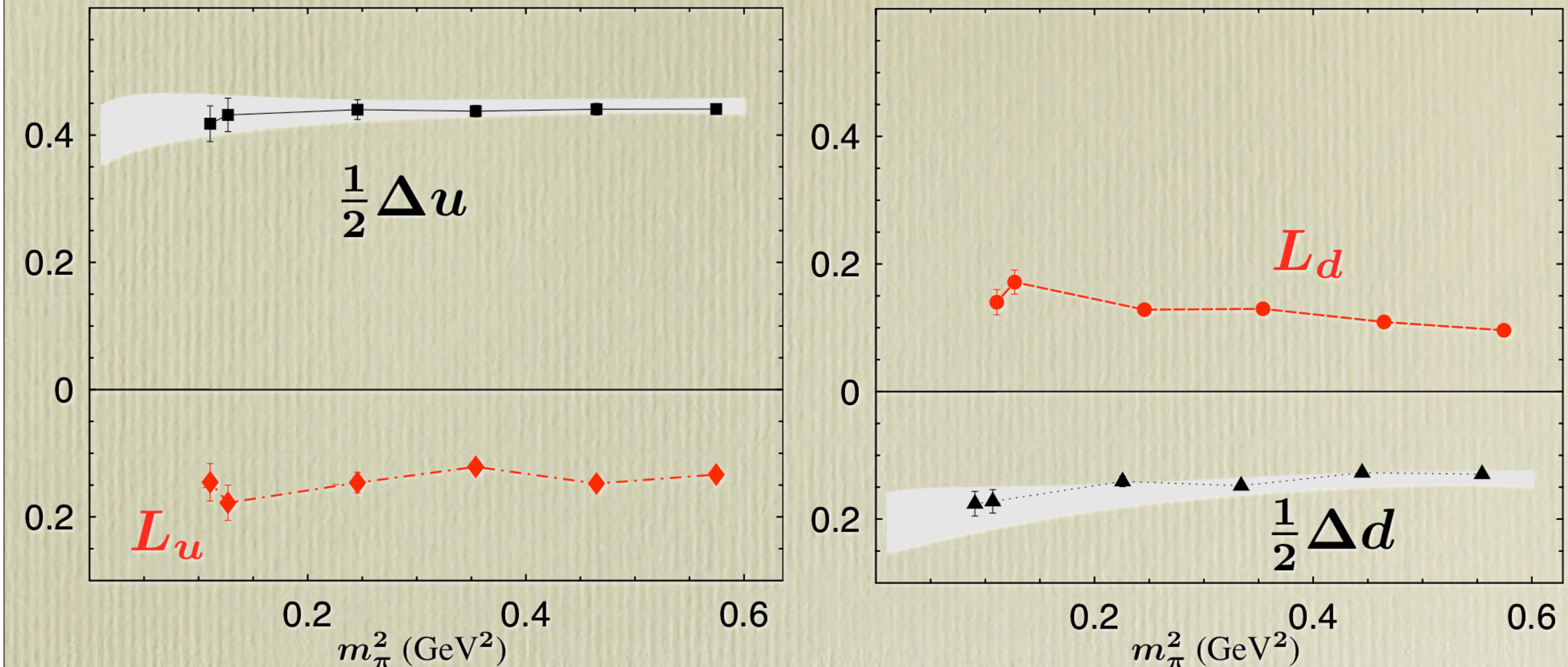
Note, $\mathcal{L}_q$ is not what appears in the parton spin audit, so the argument here is not “tight”.



P. Hägler et al, Nucleon Generalized Parton Distributions from Full Lattice QCD LHPC Collaboration, **arXiv:0705.4295** [hep-lat]

- ⋆ Disconnected diagrams are omitted so orbital angular momentum contributions of $\bar{q}q$ pairs is possible.
- ⋆ This leaves us with total gluon angular momentum as culprit in spin audit!

Hägler et al also calculate L_u and L_d separately.



The real enigma is that quark models generically predict that orbital and spin angular momentum should be parallel. So

(Ask me offline)

$$\Delta u > 0 \quad \Rightarrow \quad L_u > 0$$
$$\Delta d < 0 \quad \Leftrightarrow \quad L_d < 0$$

Note that $L_u - L_d$ is an isovector and not effected by disconnected diagrams

This is the opposite of what is seen!

Why a problem?

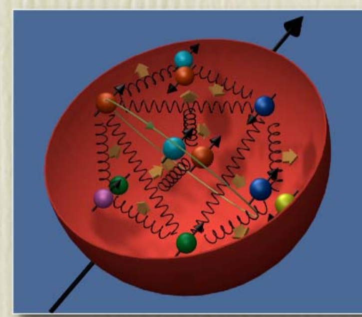
$$\Delta u > 0 \quad \Leftrightarrow \quad L_u < 0$$
$$\Delta d < 0 \quad \Leftrightarrow \quad L_d > 0$$

- Because the $L_q + \frac{1}{2}\Delta q = J_q$ it appears that the two terms cancel.
- Up to now it was possible to imagine that a vestige of the quark model survived the spin crisis by
  - § Transferring some quark angular momentum onto gluons associated with quark binding, and/or
  - § Generating quark orbital angular momentum as a consequence of relativistic structure of the Dirac equation.
- But in any independent particle model (eg. any traditional quark model) L_q and Δq are *positively correlated*.

$$q(\vec{x}) = \begin{pmatrix} f(r)\varphi_{\kappa j m}(\Omega) \\ ig(r)\vec{\sigma}\cdot\hat{r}\varphi_{\kappa j m}(\Omega) \end{pmatrix}$$

- Orbital angular momentum on $q\bar{q}$ pairs.
- Complex, correlated ground state.
- Dramatic evolution of L_q between constituent scale and scale of lattice calculation.

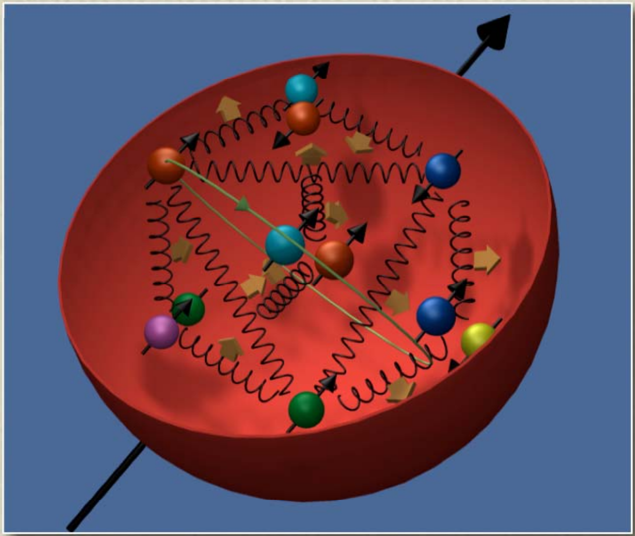
What remains of the quark model?



Everything's coming out zero!

$$
\begin{aligned}
\Delta u + \Delta d + \Delta s &\approx 0 \\
\frac{1}{2}\Delta u + L_u \equiv J_u &\approx 0 \\
\frac{1}{2}\Delta d + L_d \equiv J_d &\approx 0 \\
L_u + L_d &\approx 0 \text{ mod disconnected diagrams} \\
\Delta G &\approx \text{small}
\end{aligned}
$$

So, what remains of the quark model?
And, where is the proton's spin?



What will be the new paradigm for the quark structure of hadrons??